Development of Improved Satellite-Linked Transmitters, Physiological Recorders, and Attachment Techniques for Monitoring Beaked Whales

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LONG-TERM GOALS

We aim to improve upon our existing tagging and tracking methods for odontocetes and to develop new telemetry technology and attachment techniques that will advance researchers' abilities to understand the impacts of anthropogenic sound on odontocetes, especially beaked whales. Goal 1 is to improve upon our existing remotely-deployed satellite tag attachment technique to achieve longer monitoring periods. The design concept will follow our current design of a miniature electronics package held outside the dorsal fin by small attachment darts that penetrate the fin but do not result in a significant adverse effect on the whale. Goal 2 is the development of a new satellite transmitter in a similarly small package capable of dorsal fin attachment but with enhanced capabilities to measure and transmit behavioral information such as dive depth. Our 3rd goal is to modify existing technology for making physiological recordings and demonstrate its utility on beaked and pilot whales.

OBJECTIVES

1. Improve upon our existing remotely-deployed satellite tag attachment technique to achieve longer duration monitoring periods – aiming for up to 6 months.
2. Develop a new satellite transmitter with enhanced capabilities to measure and transmit behavioral information
3. Improve on our existing technology for making physiological recordings and test it on beaked whales or other deep divers such as pilot whales

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APPROACH

This project relies on a team approach that in addition to the PI includes Dr. Robin Baird and Greg Schorr of Cascadia Research Collective, and Dr. Brad Hanson of the NOAA Northwest Fisheries Science Center. Additionally, the engineering and other staff at Wildlife Computers are critical to the ability of this project to produce methods and tools that can be made widely available to other biologists wishing to study the movements and behavior of beaked and other whales. Short-term (hours to days) recordings from telemetry tags attached with suction-cups can provide tremendous insights, but medium to long-term observations will be needed to adequately describe the behaviors of interesting but cryptic species such as beaked whales. Our current remotely-deployed satellite tag and attachment technique using the LIMPET (Low Impact Minimally Percutaneous External-electronics Transmitter) configuration (Andrews et al. 2008) achieves attachment durations of ~ 1 month for most species, so our first objective is to improve upon this to achieve longer monitoring periods. We will empirically test attachment designs on dorsal fin tissue that we recently obtained from freshly dead stranded beaked and pilot whales. A new tag deployment device will be developed along with improved arrow designs. Our second major objective is to develop a new satellite transmitter with enhanced capabilities to measure and transmit behavioral information. We will work with a commercial telemetry manufacturer (Wildlife Computers) to develop a new tag that incorporates a depth sensor and new compression software in the same small form factor that we've been using successfully on beaked whales. Our third objective is to improve on our existing technology for making physiological recordings.

WORK COMPLETED

Our current tag attachment design consists of titanium darts with backwards facing barbs in a petal shape bent in an arc away from the shaft of the dart. To determine the efficacy of the petal barbs and their holding power, we conducted several tests with different petal materials. We decided to retain medical-grade (Gr. 5) titanium and focused on testing the effect of varying the petal material thickness. New darts were fired into rubber which simulated passing thru dorsal fin material. The change in shape of the petal and the degree of outward bend was measured to determine which petal thickness retained the most 'springy' characteristics after penetration. Tests of dummy satellite tags with various titanium dart and barb setups were conducted using dorsal fins collected from stranded animals to assess the process of dart penetration into the fin. Digital X-rays were used to assess interaction of the dart and tissue. Darts were fired into the dorsal fin, then X-rayed in-situ. The tag body and dart was then pulled backwards in line with the entry penetration, using 2 different levels of force. The amount of force exerted on the darts during these tests was not based on forces that we estimate will occur with tagged whales due to hydrodynamic drag exerted on the tag, but were chosen to try to simulate what was happening to the petals over longer periods of time with consistent drag. We first applied 11.4 kg of external force, and another series of X-rays were taken. A slight outward movement of the dart was noted upon the first 11.4 kg of pull. A second reverse pull of 22.7 kg was then exerted on the dart and further X-rays were taken.

We worked to improve the performance of the location-only satellite tag that we have been using. Cracking upon impact is a remote but worrisome possibility. To minimize the potential for cracking, the tag was strengthened with cut glass fibers added to the epoxy resin during the casting process and the manufacturing process was changed to ensure better consistency of epoxy coverage around the batteries and electronic components. Six tags of the new design were tested for robustness in impact and pressure testing. Impact testing consisted of firing the tags into a fixed, hard rubber target to

simulate the most extreme impacts the tag might encounter. All 6 tags were fired into the target between 1 and 11 times at a range of 3.5 - 5 meters. Shots were taken both in normal orientation to the target (90 degrees) and at the extreme angle of 45 degrees to target, which puts much greater forces on the darts. No visible cracks were observed. To investigate possible micro cracks, the tags were placed in a bag filled with fluorescing dye, and placed in a pressure chamber. Tags were cycled 8 times to a depth of 800 -1000+ meters, then dropped to 1000 meters and left at depth for 15 minutes. Tags were visually inspected using both a microscope and an infrared light (to fluoresce any dye intrusion). No dye intrusion was noted, suggesting no cracking during the impact testing. The new location-only satellite tags with the new dart/petal barb configuration were deployed on 4 pilot whales and 1 Blainville's beaked whale on the leeward side of the Island of Hawaii in April and May of 2009 to compare with attachment durations of the previous tag and dart petal configuration.

Another goal was to develop and test a new tag deployment device for more accurate tag delivery and attachment. Using the current Dan-Inject (D-I) airgun or crossbow system, deployment ranges were effectively limited to 20m for animals with large dorsal fins. At distances further than 20m, arrow velocity slowed down and flight was unstable, and the increased travel time to the target reduced accuracy. Several alternative tag projectors were considered. We assessed the Air Rocket Transmitter System (ARTS; Heide-Jorgensen et al. 2001) and a modified ARTS. We also investigated design changes that would improve the performance of the projector that we currently use, a modified D-I remote tranquilization rifle. Calculations suggested that enlarging the barrel diameter from 13to 20mm would result in an increase in velocity of ~ 35%, while also allowing arrow modification for better ballistics. We compared a modified, larger barrel D-I device to the performance of the Vixen Crossbow with 150lbs limbs, and a D-I JM Special 25 with a 13mm barrel, the deployment devices we typically used. Performance of the delivery devices and arrows was assessed by measuring velocities of the tag at target, and looking at ballistic trajectory and angle of impact with high-speed video.

We worked with engineers at Wildlife Computers to develop a new satellite tag capable of measuring and transmitting behavioral information such as dive depth. Eight prototypes of the new tag were successfully deployed on short-finned pilot whales in Hawai'i in 2009.

For Objective #3, in order to modify our existing technology for making physiological recordings and to demonstrate its utility on beaked and pilot whales, we began with a newly developed 8 channel archival datalogging device. We modified this device for use on beaked whales and other deep diving cetaceans to ensure it could handle deep depths and could be attached to freely-swimming whales. The device incorporated 1 Gigabyte of solid-state memory and was pressure tested to 2000 meters. Our initial design involved interfacing the data logger with an appropriate ECG electrode leads and an attachment mechanism, as illustrated in Fig. 1. After a few design iterations, we decided to put the main tag body on a tether that trailed behind the primary suction cup/electrode dart, with the secondary suction cup/electrode dart on a thinner wire positioned to be placed anteriorly on the whale's body (Fig. 2). We placed a 3-axis accelerometer sensor in the primary suction cup/electrode dart so that it would be stable, because the tethered tag body would be subject to a great deal of movement separate from the movement of the whale's body.

RESULTS

After test firing darts with various barb designs, we found that 0.020" petals compressed ~4 % less than 0.016" petals, meaning they retained their 'springiness' better than the original petals. In test shots into real dorsal fin material, we found that a slight outward movement of the dart occurred upon

the first 11.4 kg of pull (Fig. 3a, b). Analysis of the X-rays showed the petals had begun to splay outward from the dart shaft, grabbing onto the tissue as designed (Fig.3c). After 22.7 kg of pull, the petals usually splayed out further, but resisted further outward migration of the tag. The combination of the ‘springiness’ tests and the digital x-ray work led us to reduce the width of our previous petals by 20% in order to minimize tissue damage upon entry while still maintaining enough retention power. We switched to using 0.020” thick material for the primary (longer) row of petals, and 0.016” material for the secondary (shorter) row of petals.

To assess the performance of our newly modified location-only SPOT5 satellite tag and dart/petal barb design, the new setup was deployed on 4 short-finned pilot whales, 10 false killer whales, and 1 Blainville’s beaked whale in 2009. The tag attached to the Blainville’s beaked whale never transmitted, nor did one of the tags attached to a false killer whale. A few other tags have failed upon attachment with no visible sign of cracking or other malfunction and we are currently investigating potential causes of these failures. Median attachment duration of the 4 short-finned pilot whales tagged in 2009 was 62.4 days (range: 25– 110) compared to 34.9 days (range:12 – 72, n = 18) for tags of the previous construction and dart type, representing a 77% increase in duration of signal transmission, and likely tag attachment (Fig. 4) though this was not statistically significant. For false killer whales, median attachment duration of tags with the new darts was 70.7 days (range: 11– 105, n = 9) compared to 34.7 days (range: 6– 76, n = 9), a 104% increase in median transmission duration, though again, the results were not statistically different. While small sample sizes limit our statistical power, variability is also due to a number of factors including attachment location, individual tissue response, flow dynamics, and a host of other factors not yet fully understood.

We tagged 8 pilot whales with the new LIMPET Mk10-A tag (Fig. 5) on the leeward (western) coast of the Island of Hawai‘i, and transmissions lasted 4 - 47 (median 35) days. Dive data were relayed via satellite using Wildlife Computers’ new Behavior Log, providing max depth, duration, shape, and post-dive surface interval for dives > 20m, a great improvement over the traditional “histogram bins” method of data summary (see example in Fig. 6). At night, whales regularly made long (mean: 11.5 min; max: 22.4 min) deep dives between 100 and 1168 meters (mean: 359 m). Two of the pilot whales tagged with Mk10-A depth tags during the October 2009 effort were re-sighted on several occasions during the December 2009 effort. The attachment site appeared to be following the same wound healing process as for the SPOT5 LIMPET tags (Hanson et al. 2008), with small raised areas around the dart insertion sites (Fig. 5). In April 2010, a LIMPET Mk10-A depth tag was deployed on an adult female Cuvier’s beaked whale in Hawai‘i, and it transmitted for 7.2 days. Although after the end date of this ONR award, we also attached 2 LIMPET Mk10-A tags to Cuvier’s beaked whales in Southern California, and 5 LIMPET Mk10-A tags to sperm whales in Southeast Alaska. As of 30 September 2010, 1 of the Cuvier’s tags is still sending dive depth data (94 days after attachment) and 3 of the sperm whale tags are still transmitting dive data (46 days after attachment).

Delivery Device:
Velocities from the crossbow (mean =142 fps, n=26) were an average of 14 fps faster than the D-I airgun (mean = 128 fps, n = 32). Switching to a new urethane tag holder on the 13mm D-I increased velocity at target to a mean of 138 fps (n = 26). The D-I is preferred because we can reduce pressure for close shots and the long limbs of the crossbow and large amount of weight at the distal end make it more cumbersome to hold and to maneuver in a small boat. A new receiver and barrel were designed and machined to fit the existing D-I accumulation chamber and trigger housing (Fig. 7). Using an arrow of the same design used in the 13mm D-I (no flight stabilizers) and a new lighter urethane tag holder, mean velocity at target was 158 fps for the 20mm, versus 138 fps for the 13mm D-I, a 15%

increase in velocity. We created 2 arrows with different types of fletching for stabilization and tested those against the standard arrow of both the 13 and 20mm Dan-Inject rifles (Fig. 8). Velocity was not adversely affected with the addition of stabilizers, and all 3 arrow types had mean down-range velocities of 158 fps. At 25 bars firing pressure, we observed that the angle of impact appeared to be much steeper than noted for previous tests. To compare trajectory, we measured the angle of tag impact on a target, and captured the flight path from two angles using high-speed video. The mean angle of tag impact for the 13mm D-I was 15.5 degrees ‘tip-down’. We then fired the 3 different arrow types from the 20mm D-I at 25 bars (mean velocity: 158fps), and at 18.5 bars (mean velocity: 135 fps). At 25 bars, the 20mm D-I with the standard arrow had the same angle of impact as the 13mm D-I. The addition of stabilizers to the back of the arrow decreased the angle of impact from a mean of 16 degrees ‘tip-down’ to 7-8 degrees of ‘tip-down’ angle demonstrating that stabilizers do flatten the trajectory of the tag.

Physiological (ECG) recording tags:
A major challenge was the development of a method for attaching the data logger and ECG electrodes with sufficient separation between the 2 electrodes. After testing multiple alternatives, we chose a simple “T-pole” design (Fig. 2), but it does limit the electrode separation because of the curvature of a whale’s body. On our first deployment attempt on a pilot whale off of Hawai’i in December 2009, we achieved a good deployment (Fig. 9), but the tag remained attached to the whale for at least 24 hours, and overnight the whale migrated north and far out of our normal area of operation before the tag fell off. We made numerous attempts to retrieve the floating tag, but it was carried far off-shore and we were not able to recover this tag. Our 2nd deployment in Dec. 2009 was not successful in that only primary dart electrode attached firmly to the whale while the secondary dart electrode did not attach properly. The tag fell off after approximately 15 min, but the ECG channel was filled with noise because both electrodes were not firmly attached. Because of the difficulty in locating and retrieving the floating tag after our first ECG tag attachment, we modified our design to include a small Argos satellite tag (Fig. 10). We also changed our method of deployment from a single “T-pole” to 2 separate poles operated by 2 individuals. In April 2010, we made 3 deployment attempts, but in 2 cases only 1 of the electrodes was properly attached. In the 1 case where both electrodes attached firmly, 1 operator accidentally allowed the pole to come too close to the other pole and the electrode separation ended up being approximately 25 cm or less, which turned out to be too close. We could not detect any cardiac depolarization signals in the ECG, suggesting that the voltage difference between two electrodes so closely spaced on the surface of a pilot whale was not sufficient given our amplification and filtering. We are using a fairly high-gain amplifier, and any further amplification might simply magnify the muscle EMG noise without improving our ability to resolve cardiac signals. We had switched to the 2-pole method in order to make it easier to achieve greater electrode separation, and we believe that with additional practice we should be able to succeed. During our field season in April 2010, our encounter rate with pilot whales was way below our long-term average, and so we ran out of field time before we could attempt further deployments, but we are confident that additional field time will result in a successful recording of ECG from pilot whales.

IMPACT/APPLICATIONS

The development of tag technologies and deployment techniques outlined here will be make a significant contribution to the ability of researchers to track movements, monitor behavior, and determine distribution of species of interest. The improvements that we have made to our location-only satellite tag and attachment system have already resulted in attachment durations well beyond our

expectations and are currently being shared with other researchers so that they also can benefit from these advances.

TRANSITIONS

The modified location-only satellite tag was developed with engineers at Wildlife Computers and this company now offers the tag as a product for general sale. Other biologists have already purchased the satellite tag and have attached it to beaked whales in projects funded by the U.S. Navy. Further testing is being conducted on the Mk10-A depth transmitting tag and it should soon be available general sale.

RELATED PROJECTS

Although this ONR-funded project has ended, we just began a new NOPP project with ONR funding to continue this type of tag development, Grant Number: N000141010686, entitled “Improving attachments of remotely-deployed dorsal fin-mounted tags: tissue structure, hydrodynamics, in situ performance, and tagged-animal follow-up”. The National Marine Fisheries Service Pacific Islands Fisheries Science Center is supporting research on false killer whale movements in Hawaiian waters (Baird et al. 2010), and the Naval Postgraduate School (with funding from N45) is supporting tagging studies of a variety of species. Tag and deployment developments from this work are being incorporated into these ongoing studies. See www.cascadiaresearch.org/hawaii/beakedwhales.htm and www.cascadiaresearch.org/hawaii/falsekillerwhale.htm

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Baird, R.W., G.S. Schorr, D.L. Webster, D.J. McSweeney, M.B. Hanson, and R.D. Andrews. 2010. Movements of satellite-tagged false killer whales around the main Hawaiian Islands. Endangered Species Research 10:107-121.

Heide-Jørgensen, M.-P., Kleivane, L., Øien, N., Laidre, K.L., Jensen, M.V., 2001. A new technique for deploying satellite transmitters on baleen whales: tracking a blue whale (*Balaenoptera musculus*) in the North Atlantic. Mar. Mamm. Sci. 17:949–954.

PUBLICATIONS

Schorr, G.S., R.W. Baird, M.B. Hanson, D.L. Webster, D.J. McSweeney, and R.D. Andrews. 2009. Movement patterns of satellite tagged Blainville’s beaked whales off the island of Hawai’i. Endangered Species Research 10:203-213. [refereed].

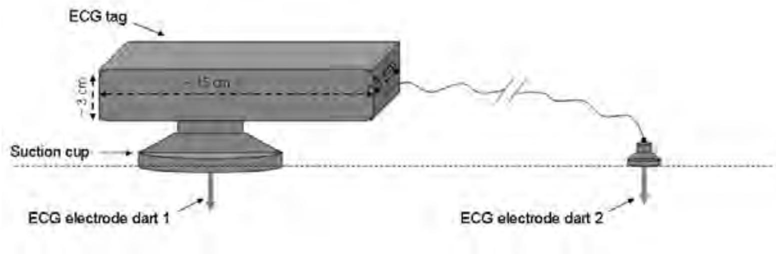

Figure 1: Preliminary design schematic for cetacean ECG tag, showing dart electrodes contained within suction cups, providing attachment strength and biopotential contact.

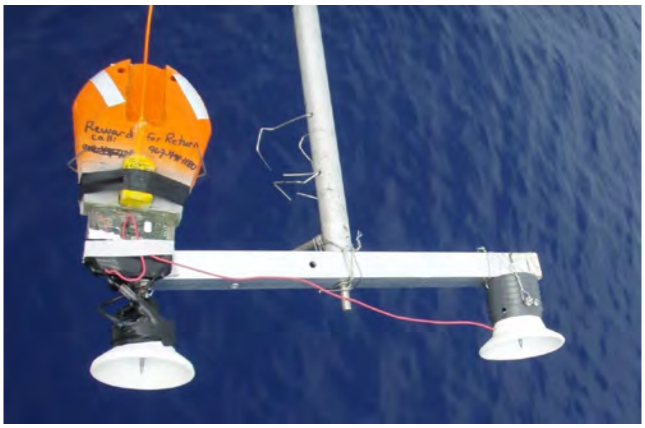

Figure 2: Modified cetacean ECG tag, with tag datalogger body tethered to the primary suction cup/dart electrode, attached to the deployment "T-pole".

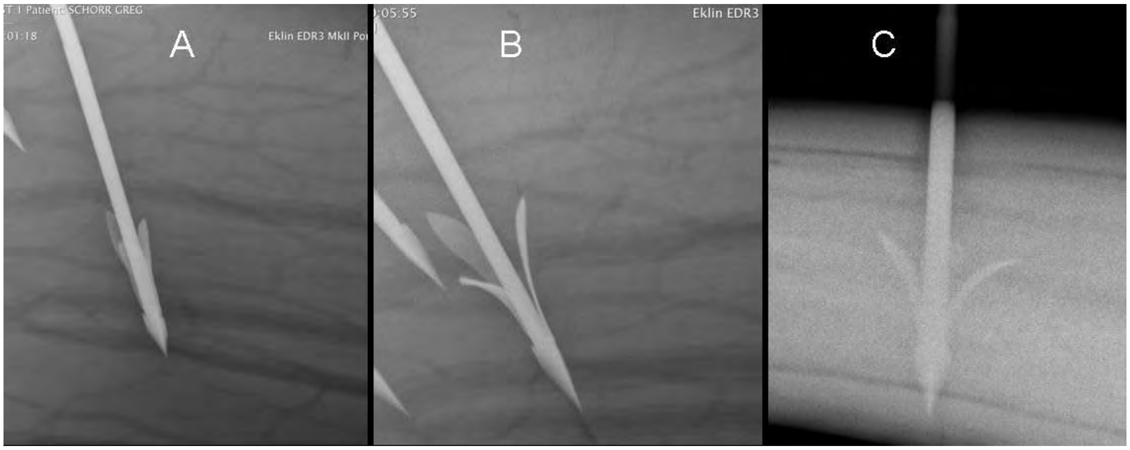

Figure 3: (A) X-ray image showing a dart in killer whale dorsal fin material after dart penetration. Note the backward facing petals are tight against the dart shaft, indicating that they were compressed upon entry into the fin which will minimize tissue damage upon entry. (B) X-ray image of the same dart in A, after 11.4 kg of outward pull was exerted on the dart shaft. Note the petals have splayed outward from the dart shaft as they cut through tissue and moved into the holding position as designed. (C) X-ray image of the same dart after 22.7 kg of outward pull. The petals have more fully splayed outward from the dart shaft and are now presenting a flat surface nearly perpendicular to the axis of outward force.

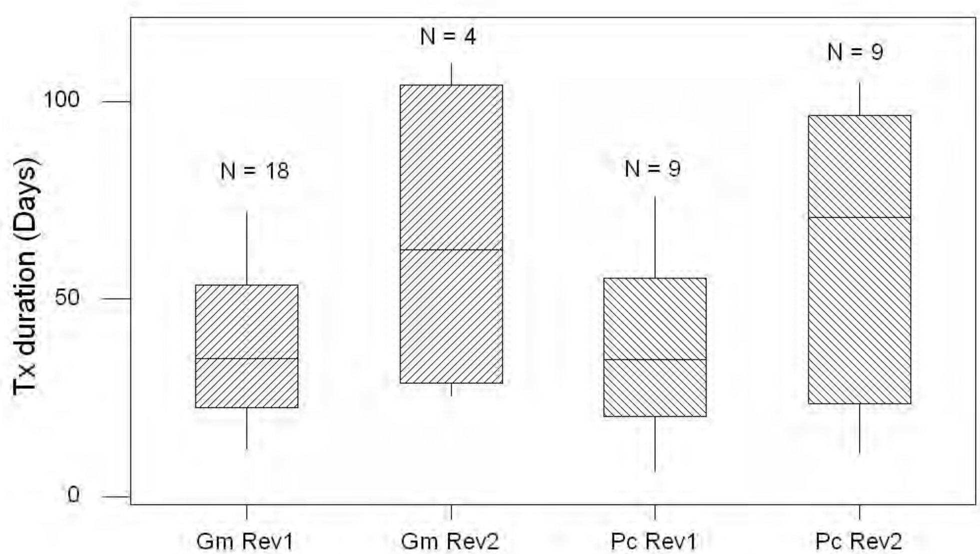

Figure 4: Box plot showing transmission duration of SPOT5 tags deployed on short-finned pilot whales (Gm) and false killer whales (Pc) with the first revision dart (Rev1) versus the second revision dart (Rev2).

Figure 5: Photograph of Gm Tag 33, with the LIMPET Mk10-A depth tag. The photo was taken 54 days post-tagging and 12 days after the last transmission. Note the discolored and slightly raised area around the dart entry sites, consistent with the findings of tissue reaction to the location only LIMPET tag.

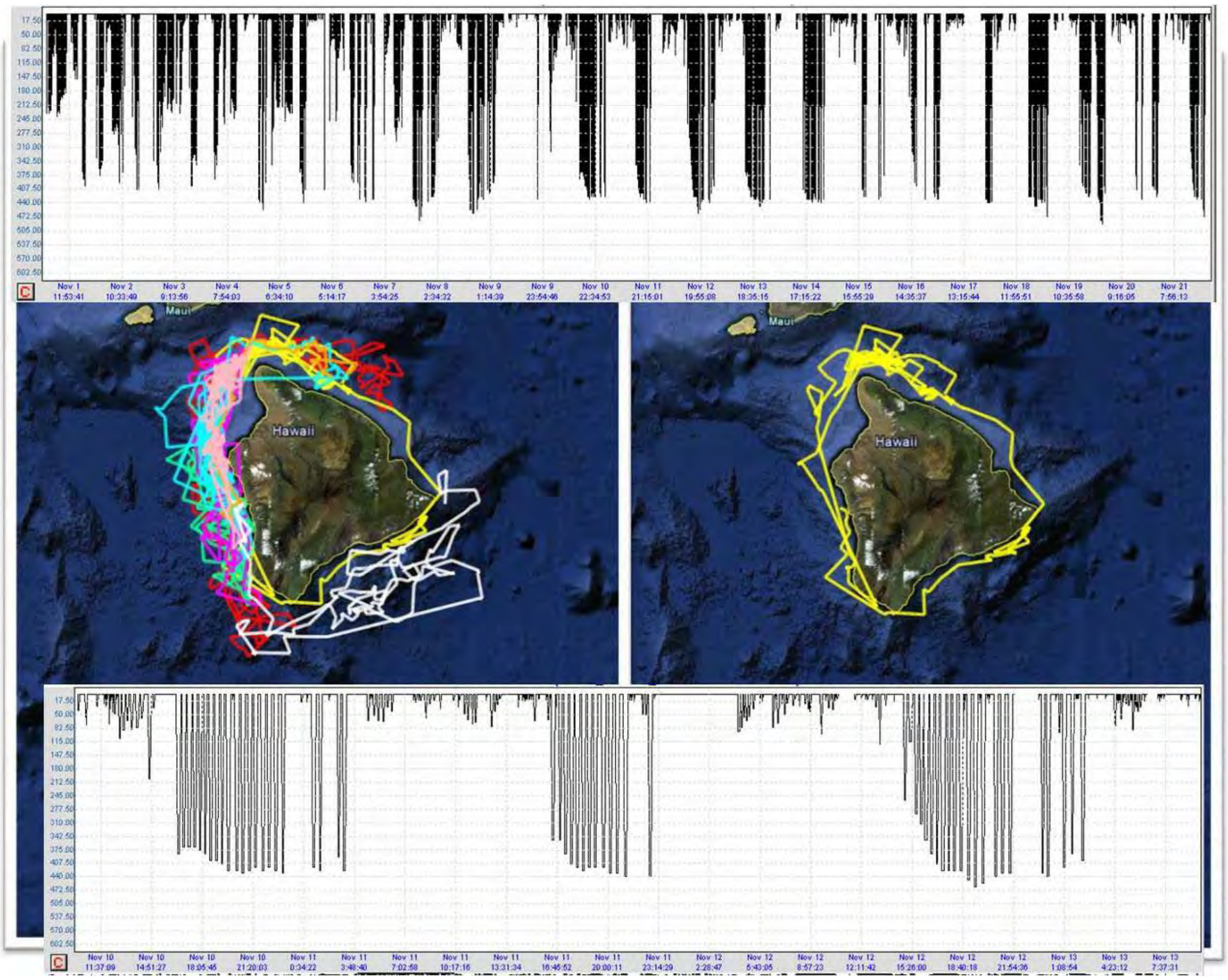

Figure 6: Top Panel – trace of dive depth over 21 days from a Mk10-A tag on pilot whale Gm35. Middle Panel Left – tracks of 8 pilot whales tagged with Mk10-A tags. Middle Panel Right – track of Gm35. Bottom Panel – zoomed in view of depth trace over 3 days from Gm35.

Figure 7: The 13mm Dan-Inject rifle on the left and the modified rifle with the 20mm barrel on the right.

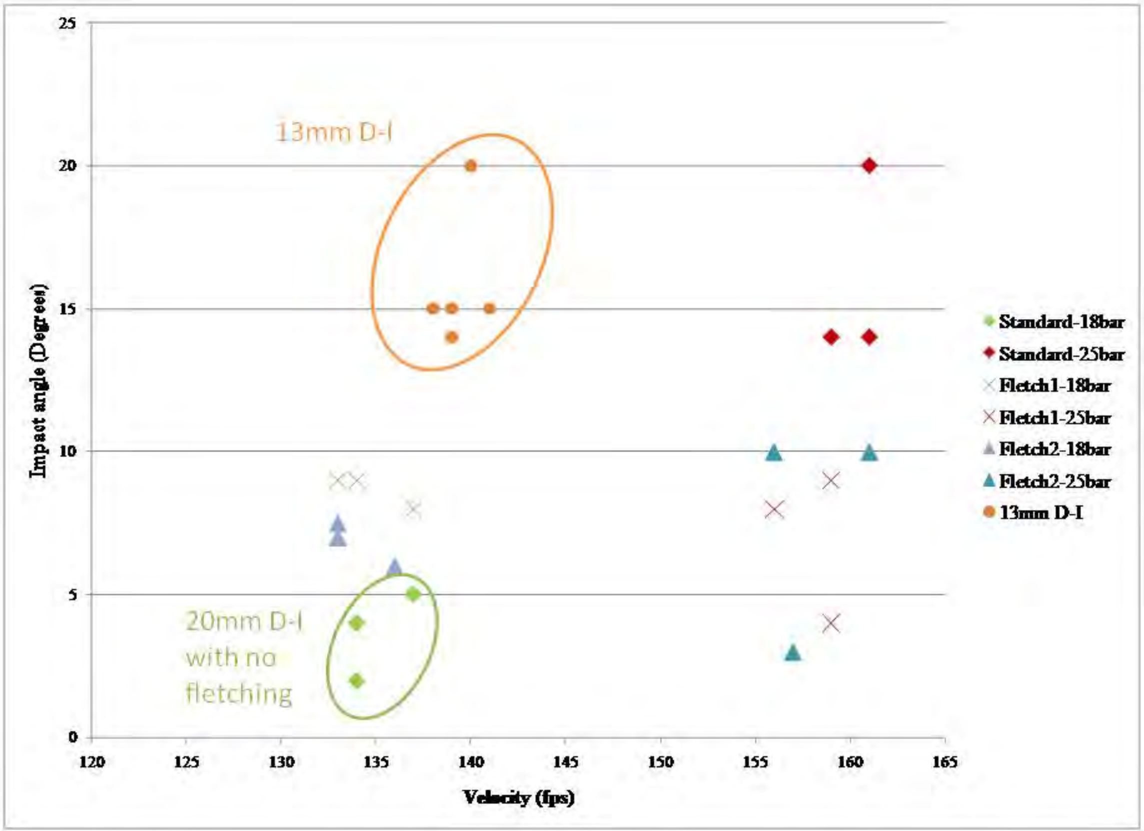

Figure 8: Results of angle of impact tests with 4 different types of arrows and 2 delivery systems. The 13mm D-I was only tested in the standard configuration which includes no addition of flight stabilizers. Three different configurations of arrows, one of which was the same design as the 13mm D-I arrow, were tested in the 20mm D-I at two pressures: 25 bars and 18.5 bars which resulted in velocities similar to those from the 13mm D-I.

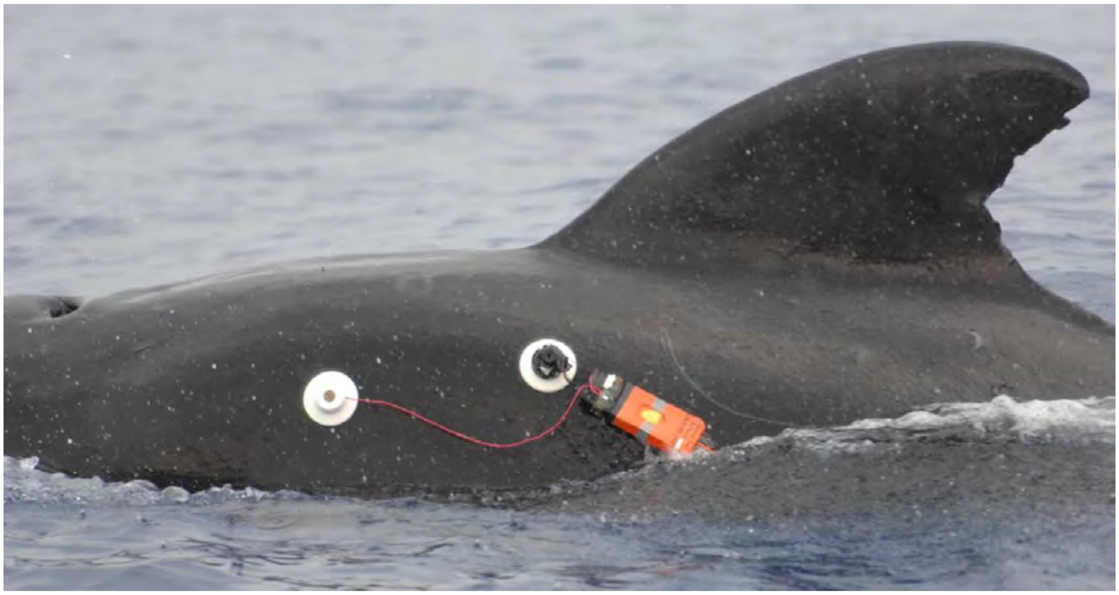

Figure 9: ECG tag attached to pilot whale off the Kona coast of Hawai'i. Tag stayed attached over 24 hours, but was never recovered.

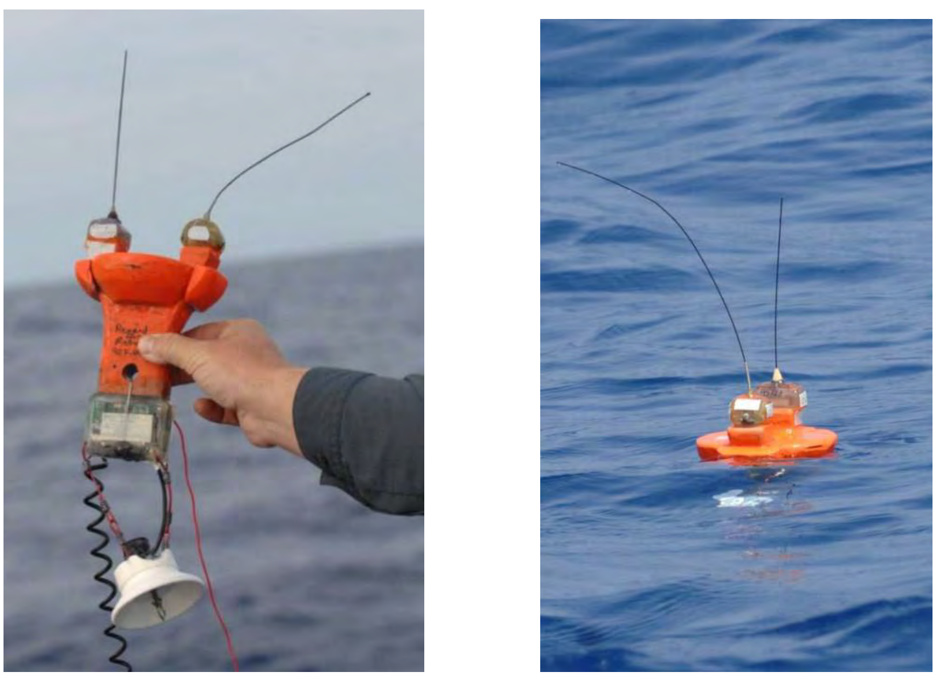

Figure 10: Modified ECG tag with VHF and Argos satellite tags.